Holographic Data Storage

Tien-Hsin chao
Jet Propulsion Laboratory
4800 Oak Grove Drive, Pasadena
California, 91109
Phone:+818-354-8614    FAX: +818-354-1545
E-mail: Tien-Hsin.Chao@jpl.nasa.gov

Presented at the THIC Meeting at the Bahia Hotel
998 West Mission Bay Dr, San Diego CA 92109
on January 16, 2001
Holographic data storage

- Hologram recording
  - fringe pattern

- Hologram readout
  - wavefront reconstruction

Signal beam $S$
Reference beam $R$
Recording medium
Readout beam $R$
Reconstructed signal beam $A$
Photorefractive Materials as Recording Medium

- Refractive index change when exposed to an intensity pattern (according to band-transport theory*):
  - Interference pattern
    
- Photogeneration and transportation of charges
  
- Space charge distribution at steady state
  
- Refractive Index modulation via electro-optic effect: space-charge field

---

Photorefractive Hologram Fixing

- **Photorefractive hologram decay/erasure:**
  - Light-induced erasure during repeat readout due to photoconductivity
    (high photoconductivity => fast photorefractive response, rapid erasure)
  - Dark decay during long-term storage due to dark conductivity
    **typical dark decay: days ~ months, depends on materials**

- **Fixing techniques:**
  - **Thermal:** heat recording medium, ~ 120°C
    for LiNbO₃, BSO, KNbO, BaTiO
  - **Electrical:** apply external electric field, ~ kV/cm
    for SBN, BaTiO, KTaNbO
  - Periodic refresh:

  ![Nonvolatile 2-photon recording](checkmark)
Thermal Fixing of Photorefractive Hologram

- Heat the recording medium during or after the normal recording process, then cool it down to room temperature (and follow with an intense uniform illumination)
  
  \[ \text{electronic charge grating copied into ionic charge grating} \]

- At room temperature, ions are “frozen”.
- At high temperature, ions become mobile and neutralize the electronic gratings (which remain relatively stable)
- When cooled down, the ionic gratings are stabilized again while the electronic ones are partially erased by an intense illumination, leaving a fixed ionic space-charge field.

- Lifetime of fixed holograms: ~ years

---

Nonvolatile Two-photon (or Gated) Recording

Recording
- First photon (e.g., uv, green) excites an electron to an intermediate state
- Second photon (e.g., red, near-IR) further promotes it to the conduction band
- The electron then migrates & gets trapped to record the interference pattern

Readout
- Readout by a single photon (e.g., red) ➞ insufficient energy to promote electron to C.B., no photoexcitation
- No erasure of data
- To erase: use both photons
Nonvolatile Two-photon (or Gated) Recording

• **To achieve two-photon recording, materials must have:**
  – Deep traps that are partially filled with electrons, and
  – Shallow (intermediate) traps to trap photogenerated electrons with sufficiently long lifetime

• **Materials for two-photon recording:**
  – Pure (undoped) PR crystals, e.g. LiNbO$_3$
    » Intrinsic defects (bipolarons induced by reduction) as intermediate states
    » Large dynamic range, low sensitivity
    » Gating light: blue laser(476nm), ~ 0.2 W/cm$^2$
    » Writing light: near-IR (800nm) Ti:sapphire, ~ 6 W/cm$^2$

  – Doped PR crystals, e.g., Fe:Mn:LiNbO$_3$
    » Extrinsic dopants (Fe$^{2+}$, Mn$^{2+}$) provide intermediate states
    » High sensitivity, small dynamic range
    » Gating light: UV (365nm) mercury lamp, ~20 mW/cm$^2$
    » Writing light: red HeNe laser, ~300 mW/cm$^2$
Nonvolatile Two-photon (or Gated) Recording

- Comparison of gate-on and gate-off readout*
  - Readout with gate off:
    - no erasure
  - Readout with gate on:
    - erasure

* undoped LiNbO$_3$, blue gating light, ~0.2W/cm$^2$
IR writing light, ~6W/cm$^2$

Nonvolatile Two-photon (or Gated) Recording

- Different readout/erasure methods in two-photon recording*
  - Erasure w/ UV and red
  - Erasure w/ UV only:
  - Readout w/ red only (partial erasure), then UV only (erasure)

* Fe:Mn: LiNbO₃,
  UV gating light, ~20mW/cm²
  red writing light, ~0.3W/cm²

Holographic Memory Light Budget

GOAL: Video-rate recording with storage capacity of 10,000 pages of 1,000x1,000 gray-scale images.

List of materials available for this application

<table>
<thead>
<tr>
<th>LiNbO$_3$ Fe</th>
<th>LiNbO$_3$ Fe, Mn</th>
<th>LiNbO$_3$ Cr, Cu</th>
<th>Green Polymer</th>
<th>Red Polymer</th>
<th>PMMA Polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>thickness</td>
<td>√</td>
<td>√</td>
<td>*</td>
<td>*</td>
<td>√</td>
</tr>
<tr>
<td>shrinkage</td>
<td>no</td>
<td>no</td>
<td>yes (3%)</td>
<td>yes (3%)</td>
<td>yes (2%)</td>
</tr>
<tr>
<td>wavelength</td>
<td>488nm</td>
<td>red+UV</td>
<td>red+blue</td>
<td>532nm</td>
<td>630-670nm</td>
</tr>
<tr>
<td>need fixing</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>dynamic range</td>
<td>large</td>
<td>large</td>
<td>large**</td>
<td>modest</td>
<td>modest</td>
</tr>
<tr>
<td>wiring speed</td>
<td>slow</td>
<td>very slow</td>
<td>slow**</td>
<td>very fast</td>
<td>fast</td>
</tr>
<tr>
<td>rewritable</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

* Thin materials only. Large-scale storage might be problematic with non-mechanical scanners.

** Projected.
For non-volatile storage of 10,000 holograms, the target diffraction efficiencies are,

\[ \eta_h = \left( \frac{M/#}{M} \right)^2 \]

<table>
<thead>
<tr>
<th></th>
<th>LiNbO₃ Fe</th>
<th>LiNbO₃ Fe, Mn</th>
<th>LiNbO₃ Cr, Cu</th>
<th>Green Polymer</th>
<th>Red Polymer</th>
<th>PMMA Polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>M/#</td>
<td>10*</td>
<td>10</td>
<td>30**</td>
<td>6</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>( \eta_h )</td>
<td>2.5x10⁻⁷</td>
<td>10⁻⁶</td>
<td>10⁻⁵**</td>
<td>3.6x10⁻⁷</td>
<td>2.5x10⁻⁷</td>
<td>2.5x10⁻⁷</td>
</tr>
</tbody>
</table>

* The M/# drops approximately by a factor of 2 after thermal fixing in LiNbO₃:Fe.
** Projected value.
1. Photon-limited readout:

\[
N_e = \eta_{tr} \eta_q \eta_h \eta_{im} \frac{P_{in}}{h\nu} \frac{1}{r_{ON} N_p} t_{int}
\]

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ne</td>
<td>number of signal electrons</td>
<td>~25,000*</td>
</tr>
<tr>
<td>(\eta_{tr})</td>
<td>electron transfer efficiency</td>
<td>0.9**</td>
</tr>
<tr>
<td>(\eta_q)</td>
<td>quantum efficiency</td>
<td>0.9</td>
</tr>
<tr>
<td>(\eta_h)</td>
<td>hologram diffraction efficiency</td>
<td>From above</td>
</tr>
<tr>
<td>(\eta_{im})</td>
<td>efficiency of readout optics</td>
<td>0.9</td>
</tr>
<tr>
<td>(P_{in})</td>
<td>readout power</td>
<td>?</td>
</tr>
<tr>
<td>(h\nu)</td>
<td>power per electron</td>
<td>4.073x10^{-19} J</td>
</tr>
<tr>
<td>(r_{ON} N_p)</td>
<td>number of ON pixels</td>
<td>0.5x10^6***</td>
</tr>
<tr>
<td>(t_{int})</td>
<td>integration time</td>
<td>1 sec.</td>
</tr>
</tbody>
</table>

• For binary data, 100 photoelectrons at a pixel are needed for optimal hard thresholding, considering electronic, optical, and holographic noise.
  
  **  Worst-case transfer efficiency from CCD to external electronics.
  
  *** Exact number for binary random-bit patterns.
<table>
<thead>
<tr>
<th></th>
<th>LiNbO$_3$ Fe</th>
<th>LiNbO$_3$ Fe, Mn</th>
<th>LiNbO$_3$ Cr, Cu</th>
<th>Green Polymer</th>
<th>Red Polymer</th>
<th>PMMA Polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{in}$ (mw)</td>
<td>28</td>
<td>7</td>
<td>0.07*</td>
<td>19</td>
<td>28</td>
<td>28</td>
</tr>
</tbody>
</table>

**Readout powers for 1-second integration time**

**Recording speed**

1. recording speed for 10,000 holograms (target diffraction efficiency is $10^{-7}$).

<table>
<thead>
<tr>
<th></th>
<th>LiNbO$_3$ Fe</th>
<th>LiNbO$_3$ Fe, Mn</th>
<th>LiNbO$_3$ Cr, Cu</th>
<th>Green Polymer</th>
<th>Red Polymer</th>
<th>PMMA Polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Writing energy mj/cm$^2$</td>
<td>3</td>
<td>100*</td>
<td>1**</td>
<td>0.1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Writing intensity mw/cm$^2$</td>
<td>100</td>
<td>333*</td>
<td>33**</td>
<td>3.3</td>
<td>80</td>
<td>80</td>
</tr>
</tbody>
</table>

* For recording at He-Ne line. Data for blue recording is not available at the moment.
** Projected value.
Objectives and Major Products

• UPN 632 Micro/Nano Sciencecraft Thrust

  • Task Purpose: Objectives:
    • Develop innovative nonvolatile, large-capacity, high-speed, read/rewrite compact holographic data storage system: Ultra High data/image storage capability (1TB);
    • High-speed random access data transfer (1GB/s)

  • Major Products:
    • A compact holographic data storage with 10 GB non-volatile random access memory per cube with potential of reaching 1 TB memory board by stacking 10 x 10 cubes.
Objectives:

- **Develop innovative memory technologies to enable large-capacity, high-speed, read/rewrite of image and digital data in a space environment**
- **Demonstrate key capabilities:**
  - Ultra High data/image storage capability (1TB)
  - High-speed random access data transfer (1GB/s)
  - Radiation-resistance

Product Breakdown Structure:

- A compact holographic data storage with 10 GB non-volatile random access memory per cube
- Up to 10 x 10 cubic memory can be stacked into an ordinary memory board size to achieve a storage capacity of 1TB
- Read/rewrite, rad hard, high transfer rate
Comparison of CHDS Technologies

Pros
- AO device mature
- High-speed
- Medium density (x1 AO)

Cons
- Bulky (AO device requires lens set for beam forming)
- High-density storage requires 2 cascaded AO, very difficult for miniaturization

Pros
- Very compact using VECSEL array for multiplexing
- High-speed
- Medium density

Cons
- High-density storage requires high-density VECSEL array
  - 10 x 10 array available to date
  - with only 4 mW power for each laser source (1/20 of needed power)

Pros
- Very compact using BS device
- High-speed
- High density achievable with using 2 cascaded BS devices
- Use 2 single diode laser (commercially available)
- BS device is an emerging technology with a road map for performance optimization
READ-WRITE HOLOGRAPHIC MEMORY CUBE

MEMORY OPERATION

- HIGH DENSITY COMPACT READ-ONLY MEMORY
  - 10,000 PAGES OF HOLOGRAM PER CUBIC INCH
  - 10 GBYTES STORAGE CAPACITY
  - UP TO 1000 PAGES PER SECOND READOUT RATE
- LOW VOLUME, MASS, POWER CONSUMPTION
- LENSLESS CONFIGURATION RESULTS IN DISTORTION-FREE DATA AND IMAGE RECALL
- VECSEL laser array not mature yet, 10 x 10 array with 4 mw each laser source is available now
System Schematic of an Advanced CHDS Architecture

Unique Advantages

• **Very compact**
  – Cubic package with the size of a cigarette box

• **Massive data storage**
  – store up to $10^4$ pages of hologram with 10 Gbytes capacity

• **High-speed**
  – current throughput 200 Mbytes/sec achieved with using a LC Beam Steering Device. Could be 10x faster if FLC is used

• **Device/components maturity**
  – Use two single diode lasers that are commercially available at low cost
  – Beam Steering Device is a emerging technology. JPL is actively engaged with BNS in developing the next generation high-speed version
Liquid crystal phased array beam steering device

- Beam steering based on optical phase modulation

Optical phase profile (quantized multiple-level phase grating) repeats every 0-to-$2\pi$ ramp with a period $d$ which determines the deflection angle $\theta$. 
Liquid crystal phased array beam steering device

• Diffraction efficiency:

\[ \eta = \left( \frac{\sin(\pi/n)}{\pi/n} \right)^2 \]

\( n \): number of steps in the phase profile
\( e.g., \eta \sim 81\% \) for \( n = 4 \), \( \eta \sim 95\% \) for \( n = 8 \)

• Deflection angle:

\[ \theta = \sin^{-1}(\lambda/d) \]

for the first order diffracted beam

• Number of resolvable angles:

\[ M = 2m/n + 1 \]

\( m \): pixel number in a subarray
\( n \): minimum phase steps used

\( e.g., M = 129 \) for \( m = 512 \), \( n = 8 \) with a 1x4096 beam steering device
Photograph of a Liquid Crystal Beam Steering Device

Surface phase-modulation profile of a beam steering device
Cascaded beam steering architecture:

- Liquid crystal phased array beam steering device

Input beam

$M_1$-angle 1-D beam steerer

$M_2$-angle 1-D beam steerer

$M_1 \times M_2$ 1-D or 2-D output beam directions

Total resolvable angles of more than 10,000 can be easily achieved.
Liquid crystal phased array beam steering device

Benefits of using LC SLM beam steering devices:

- No mechanical moving parts
- Randomly accessible beam steering
- Low voltage / power consumption
- Large aperture operation
- No need for bulky frequency-compensation optics as in AO based devices
Performance Characteristics of LC Beam Steering Device

- Number of pixels: 4096 Reflective
- VLSI backplane in ceramic PGA carrier
- Array size: 7.4 x 7.4 mm
- Pixel size: 1µm wide by 7.4mm high Pixel pitch: 1.8 µm
- Response time:
  - 200 frames/sec with Nematic Twist Liquid Crystal
  - 2000 frames/sec with Ferroelectric electric Crystal (under development)
An acousto-optics based Holographic Data Storage Breadboard developed in FY 1999.

**FY 2000 product: A book-sized CHDS breadboard**

*Total Volume: 9.5” X 6.5” X 2.5”*
New 512 x 512 Grayscale Spatial Light Modulator

- New Grayscale SLM has been developed by Boulder Nonlinear System Inc. under a NASA/JPL SBIR Phase II program (T.H. Chao is the JPL contract monitor)
  - 512 pixel x 512 pixel, 7-µm pixel pitch, 3.6 mm x 3.6 mm aperture size
  - High-speed at 1000 frames/sec
  - Enable high-density, high transfer rate data storage
  - Enable further system miniaturization

Photo of the new FLC SLM, much smaller than a dime

A high-quality grayscale image readout from the SLM
Holographically Retrieved Grayscale Images
- Asteroid Toutatis

Input Images

Retrieved Holographic Images
Holographically Retrieved Grayscale Images
- Asteroid Toutatis

Input Images

Retrieved Holographic Images
System architecture of an optical correlator using holographically stored and retrieved filter data for real-time optical pattern recognition. (a) A grayscale optical correlator and (b) an AO based holographic memory system.
Example Training Image Set and Corresponding MACH Filter Image
A camcorder-sized Grayscale Optical Correlator Developed at JPL

PRIMARY FEATURES

- CAMCORDER SIZE (8” X 4” X 4”),
- ULTRAHIGH SPEED (1000 FRAMES/SEC), 30 TIMES FASTER THAN VIDEO RATE
- GRAYSCALE RESOLUTION (8 BIT INPUT, BIPOLAR 6 BIT FILTER)
- DIRECT COUPLED TO VIDEO SENSOR
- REAL-VALUED FILTER MODULATION ENABLES SMART FILTER ENCODING
Experimental Result of MACH Filter Storage/Retrieval

- A MACH filter, capable of recognizing a class of airplane images, to be stored into the holographic memory.
- The MACH filter image, retrieved from a holographic memory.
FOR THE FIRST TIME, JPL DEVELOPED A GRAYSCALE, COMPACT, AND ULTRAHIGH SPEED OPTICAL PROCESSOR AND DEMONSTRATED FOR AUTOMATIC TARGET RECOGNITION (ATR)

PRIMARY FEATURES

– REAL-TIME AUTOMATIC TARGET DETECTION AND RECOGNITION FOR BMDO
– CAMCORDER SIZE (8” X 4” X 4”),
– ULTRAHIGH SPEED (1000 FRAMES/SEC), 30 TIMES FASTER THAN VIDEO RATE
– UNIQUE GRAYSCALE RESOLUTION ENABLES HIGH DISCRIMINATION AND INVARIANCE IN A CLUTTERED/NOISY BACKGROUND

APPLICATIONS

• REAL-TIME ON-BOARD ATR FOR
  – CRUISE MISSILE DEFENSE
  – MISSILE SEEKER AIMPOINT SELECTION

JPL developed camcorder-sized Grayscale Optical Correlator - Funded by BMDO / IS&T

1998 Real-time field tech demo for real-time target recognition and tracking of a Vigilante test vehicle (at Mojave, CA) using JPL’s optical correlator
Pattern Recognition Demonstration Using A Holographically Retrieved Filter in an Optical Correlator

- Real-time Recognition and Tracking of a Flight Test Vehicle With Different Scale, Orientation, and Background Clutter
Pattern Recognition Demonstration Using A Holographically Retrieved Filter in an Optical Correlator - Continued